High-Fidelity Finite-Element Modeling of Shallow-Water Target Scattering

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Award Numbers: N0001405WX20436, N0001405WR20289
Note: Both document numbers funded this project.
http://www.ncsc.navy.mil

LONG-TERM GOALS

The goal of this three-year effort is to develop a state-of-the-art, high-fidelity, finite-element, broadband computer simulation capability for modeling the scattering of sonar signals by undersea mines located in or near the seabed in littoral environments with smooth or rippled water/sediment interfaces. The target models will include all internal and external structural details that significantly affect the scattered field.

OBJECTIVES

The project will employ four large software systems (described below); all are separately operational today. The primary objective is to bring it all together in a computationally efficient, user-friendly manner, which will provide the U.S.Navy with a powerful MCM simulation tool, readily available to scientists at any laboratory, on virtually any computer platform, at modest cost. The secondary objective is to maintain a continuing R&D effort to improve the underlying mathematics, physics and/or numerical algorithms in each component system in order to keep the technology at the forefront of computational techniques.

APPROACH

- **Multiscale**

Modeling 3-D target scattering in a littoral environment is a multi-scale problem, both spatially and temporally. Spatially, dimensions range from O(10^{-2} m) for structural details of realistic targets to O(10^{3} m) for the littoral ocean environment (Fig. 1). Temporally, the acoustic sources are broadband, with frequencies ranging from O(10^{3} Hz) to O(10^{5} Hz), with an even greater range of wavelengths due to the presence of evanescent waves in and next to the target. These spatial and temporal multiscale features necessitate a variety of different computational strategies, described under Work Completed.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **High-Fidelity Finite-Element Modeling of Shallow-Water Target Scattering**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center,110 Vernon Ave.,Panama City,FL,32407**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

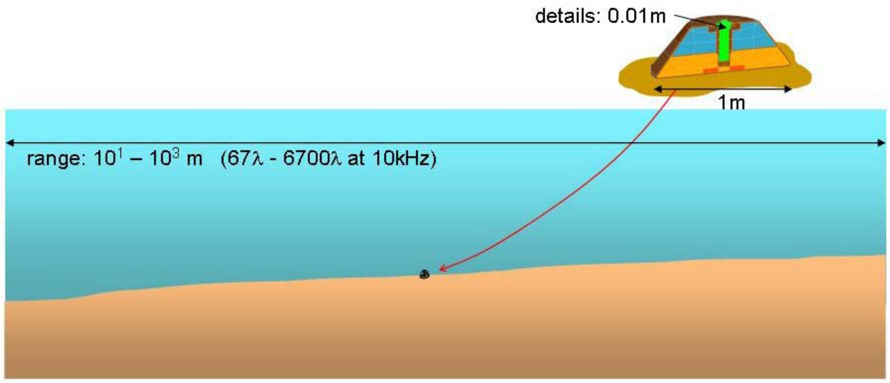

Fig. 1. Typical range of scales in a littoral scattering problem

- **High fidelity**

To achieve a high-fidelity model of elastic-wave propagation in a mine, the models will employ 3-D continuum mechanics for every part of the mine. Thin structural components, such as plates and shells, will be modeled with 3-D elasticity theory, rather than plate or shell theories (the latter being 2-D physics inside 3-D geometry). This use of 3-D elasticity for thin structural components, rather than the traditionally and universally used plate and shell theories, is a special feature of this project. Burnett has had extensive and very successful experience since the mid-1980s developing large FE codes based on this 3-D physics philosophy [1].

- **Verification and validation**

The control of errors, via verification and validation, plays a key rôle in this project; it is essential to the goal of providing reliable simulations of the real world. Verification refers to the control of errors in the finite-element solution vis-à vis the exact solution of the idealized mathematical model, i.e., computational/mathematical errors. Validation refers to the control of errors in the exact solution of the idealized mathematical model vis-à vis the real world, i.e., errors in the physical asumptions and data in the idealized model. V&V, as it is popularly referred to, is an ongoing, never-ending exercise as the simulation capabilities mature.

- **Key individuals**

  - Dr. David Burnett (NSWC-PC): PI - overall responsibility for conceptual design of simulation software and finite-element technology
  - Dr. Kwang Lee (NSWC-PC): modeling and programming
  - Dr. Quyen Huynh (NSWC-PC): preconditioning for iterative solvers
  - Dr. Gary Sammelmann (NSWC-PC): interfacing FE targets with PC-SWAT for very-large-scale, realistic littoral models
  - Dr. Jari Toivanen; Prof. Kazufumi Ito (NC State Univ): interfacing FE targets with very fast solvers for large-scale, high-fidelity littoral models

WORK COMPLETED

The principal goal for FY05 was to develop the conceptual design for the above-described simulation system, acquire the necessary software, become familiar with the software and its limitations, work on improving the limitations, and investigate procedures for how it will all couple together. This was accomplished and the result is shown in the flowchart in Figure 2, which represents a high-level summary of the year's work.

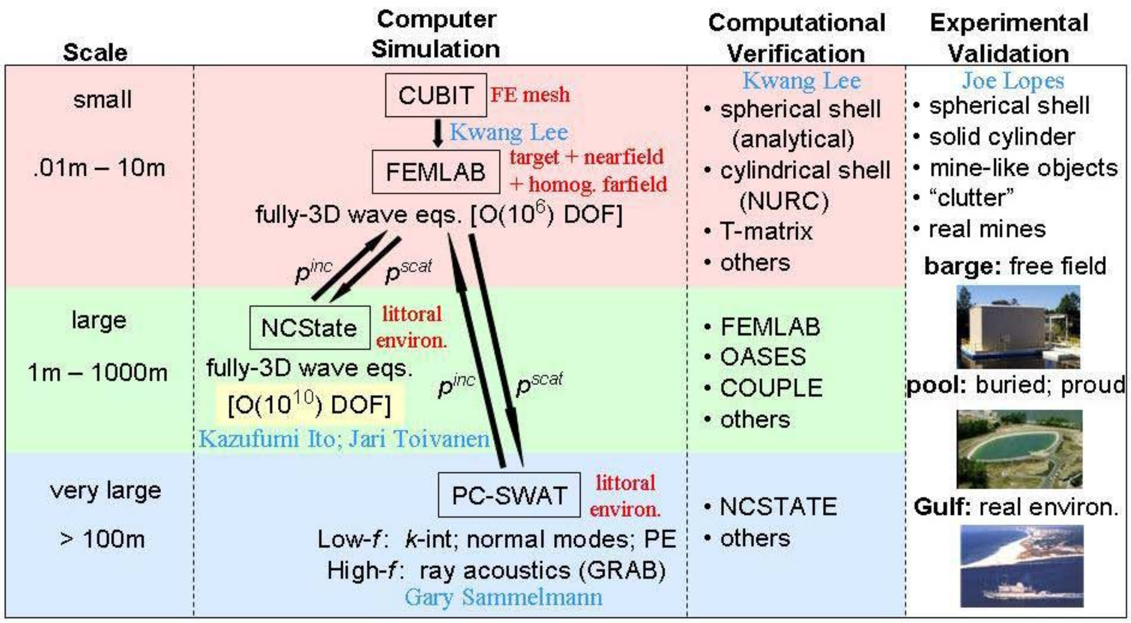

Fig. 2. Four software systems for modeling different spatial scales; their interrelationship; verification and validation tasks

The left column shows the approximate ranges for "small", "large", and "very large" scales. The three scales intentionally overlap, providing a means for verifying the systems with each other. The second column shows the four software systems that will be used to handle the three spatial scales. All four systems are *separately* operational today. The arrows indicate how the four systems will interact. (Creating these interfaces will be the principal goal in FY06.) The planned tasks for verification and validation are indicated in the third and fourth columns. Verification logically precedes validation. Validation will proceed vertically downward, beginning with just the target itself, i.e., in the free field, then adding a *controlled* environment, and finally adding a large-scale *real* environment.

FEMLAB will model the target and a small volume of surrounding water and sediment. CUBIT will generate meshes for FEMLAB. The label "NCState" refers to a littoral propagation code developed at N.C. State Univ.; it employs a "breakthrough" FE technology for modeling the fully-3D Helmholtz equation over large scales. PC-SWAT is well-known to ONR and the Naval community; it employs a rich set of physical phenomena and can model very large scales.

RESULTS

- **FEMLAB**

FEMLAB is a general-purpose, multi-physics FE code developed by Comsol, Inc., in Stockholm, Sweden. This code has many attractive features for high-fidelity 3-D modeling of wave propagation in solids and fluids. Several verification studies have already been performed, one of which is illustrated in Fig. 3, which shows a model of scattering of a plane wave from an elastic spherical shell at the dimensionless frequency of $ka = 10$, along with a comparison with the exact analytical solution.

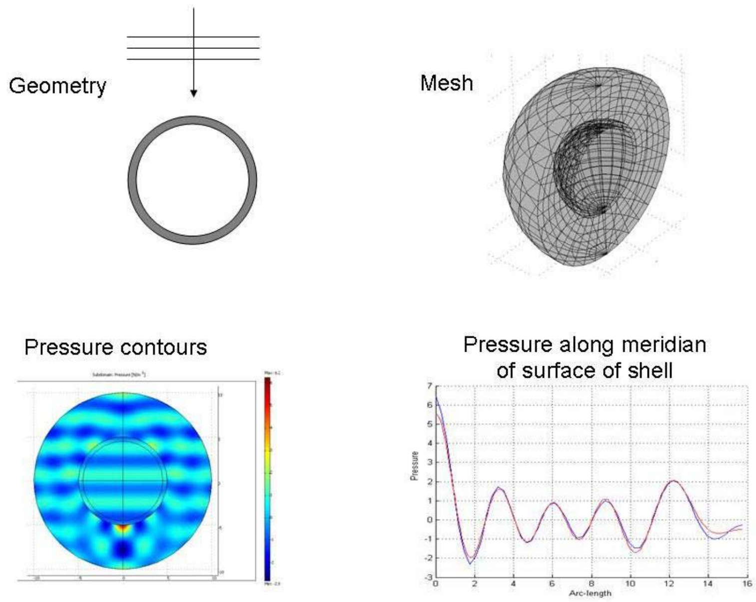

Fig. 3. Verification: Scattering of plane wave by elastic spherical shell

Burnett has engaged in considerable communication with the developers (in Stockholm) to speed up solution time in FEMLAB. This led to two enhancements:

1. Using a GMRES iterative solver with a geometric multi-grid preconditioner.
   This speeded up cp time by an order of magnitude relative to the default sparse direct solver. As the model size increases, the speedup increases further.

2. Enhancing their radiation absorbing boundary conditions from 1^{st} to 2^{nd} order.
   This permits reducing the size of the water mesh surrounding the target, which significantly reduces cp time.

- **CUBIT**

CUBIT is a powerful, user-friendly, 3-D "all-hex" mesh generator developed by Sandia Laboratories for the DoE and therefore license-free to government labs and universities. Investigations by Sandia and Comsol indicated CUBIT and FEMLAB would be compatible. NSWC-PC obtained a copy of CUBIT and has started to develop some meshes. Figure 4(a) shows a mesh of (half) an elastic cylinder

with hemispherical endcaps, surrounded by a sphere of water, and 4(b) shows a mesh of the fiberglass casing of a Manta mine and some internal structural features.

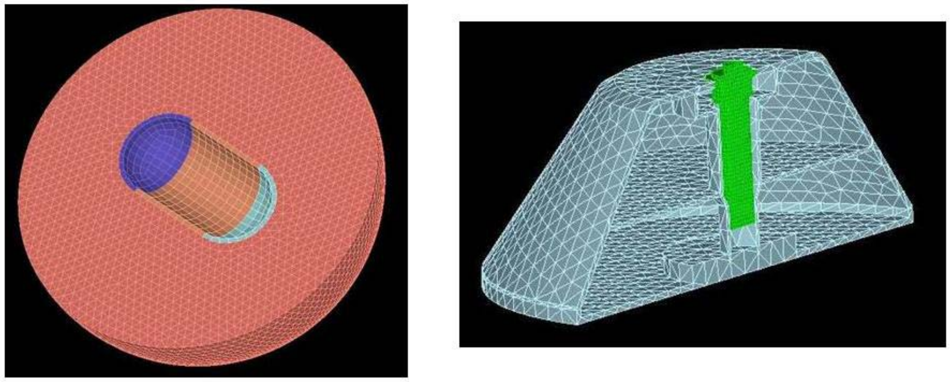

Fig. 4. (a) Mesh of half an elastic cylinder with hemispherical endcaps, in water; (b) mesh of a Manta mine casing and some internal features.

- **N.C. State code**

The Fictitious Domain Method (FDM) originated in Russia, evolved in Finland and elsewhere and has been under further development at N.C. State [2]. It is apparently the first-ever application of FE methods to modeling the 3-D Helmholtz eq. in acoustically-large bounded domains (dimensions 100s to 1000s of λ). All methods developed heretofore, a.k.a. "propagation codes", make simplifying approximations to the underlying physics (e.g., range independence, flat bottom, no back scatter, etc.). The FDM applied to acoustic scattering problems will, for the first time, provide a large-scale propagation modeling capability that does not make any simplifying physical approx-imations. Hence it will provide a *high-fidelity* littoral propagation modeling capability.

The FDM is clearly a breakthrough technology: it can currently solve problems with several *billion* DOF on a *single-processor PC,* in a few tens of hours. N.C. State believes that improving the current algorithms can decrease cp times an order of magnitude. In addition, since the FDM can be parallelized, decreases of more orders of magnitude are possible. Thus, this project has the realistic potential to launch a "new era" in high-fidelity modeling of scattering from complex targets in littoral environments**.**

The FDM has higher fidelity physics than PC-SWAT, but is much slower. It will complement PC-SWAT by (i) modeling complex littoral environments with higher fidelity, and (ii) benchmarking PC-SWAT to quantify its modeling errors, making the latter both a *reliable* and fast code.

Figure 5 illustrates a very large 3-D problem that the FDM solved for this project. It models a large cube of water and sediment in the center testing area of the NSWC-PC test pool, with a Manta-shaped

hole under the water/sediment interface and a 10 kHz monople source. The model required 3.4 billion equations and was run on a Dell PC.

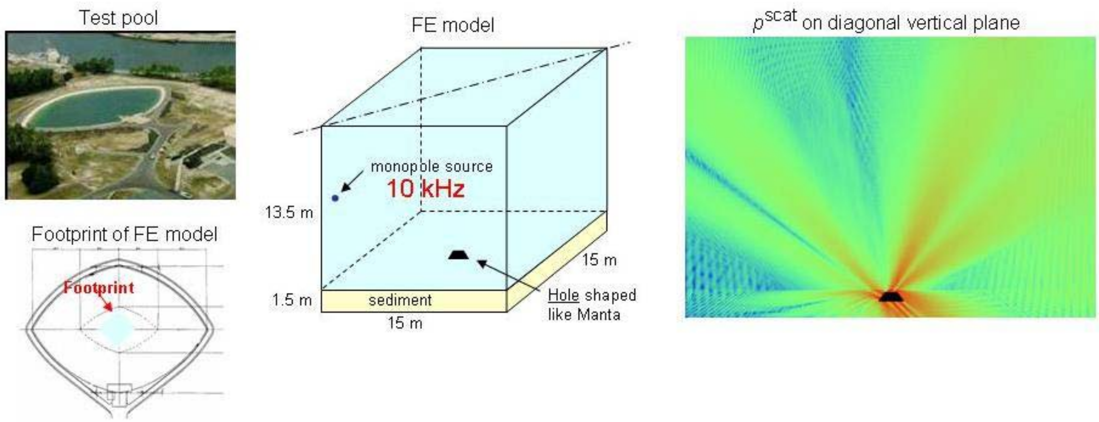

Fig. 5. A fully-3D FE analysis of scattering from a buried mine-like object.

- **PC-SWAT**

The PC-SWAT code, developed by Gary Sammelmann at NSWC-PC, is well-known in the ONR community, with many publications [3]. During FY05 Burnett and Sammel-mann discussed technical approaches for coupling FEMLAB target models with PC-SWAT. It was decided to use an admittance matrix, a.k.a. Green's function, technique.

IMPACT/APPLICATIONS

This multiscale simulation system will be an important component of acoustic MCM systems developed by, e.g., SWAMSI, BMC and SAX04, since the reliability of detection and classification algorithms depends significantly on the accuracy of predicted signatures of targets of interest. The scientific impact will be the knowledge and insights gained regarding the physics of wave scattering by complex targets and how structural parameters such as geometry and material properties influence that phenomenology.

RELATED PROJECTS

The ONR SAX04 program.   During FY05 Burnett participated in SAX04 workshops but had no direct funding from that program. However, direct funding for FY06 – 08 will be available. Therefore this simulation technology will be used to support that work. In particular, Eric Thorsos (PI) needs "rigorous simulations" of buried cylindrical targets.

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